

# Evangelos Anastassakis: Scientist, Colleague and Friend

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## 1 Evangelos, the Friend

I first met Evangelos at the University of Pennsylvania in the Fall of 1969. Fred Pollak and I had started setting up a Raman laboratory at Brown University and, given Fred's interest and experience in uniaxial stress techniques, we had decided to launch a program for measuring the effect of such stress on Raman phonons in solids, in particular semiconductors. We decided to begin with silicon. The pressure and sample preparation equipment was readily available at Brown but we had to wait for the Raman equipment and the funds to pay for it (which we got, in due course, from the University Administration!). At some conference we met Eli Burstein, with whom I had a long friendship dating back to 1958 (I was in 1958 a graduate student and Eli already a big man in Solid State Physics. I was impressed ever since by his way of treating me as an equal). Evangelos, then called by us "Van", may well have been present at the meeting. Eli suggested that what we should do is bring prepared samples and the pressure rig (we had to watch out not

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to call it "bomb" so as to avoid a *faux pas* at the airports) and perform the measurements in Philadelphia using his hand-made Raman spectrometer (built by a highly skilled technician named Aron Filler). We agreed and Fred and I went to Philadelphia and worked with "Van" and Aron Pinczuk day and night, pressing Eli into giving us as much time as he could as a busy professor.

I believed that one round of measurements of a few days would be sufficient to collect the data needed to write the first experimental paper on the matter. It took two rounds for Evangelos to write the first draft. It was not the first paper Evangelos had written. He had received his Ph.D. at Penn in 1968 and had already published or sent for publication eight manuscripts. He knew very well the ins and outs of Eli's spectrometer (very important when dealing with homemade instruments!) and pitched in day and night to try to finish the project as soon as possible.

The only anecdote I remember from those days is his leaving the side of the instrument (those days such instruments were seldom left to take data by themselves) to answer a phone call. He spoke Greek and sounded very upset. All I was able to understand is his repeated expletive: "katastrophia". The call was long and we were quite concerned about his getting rather pale. When he hung up and we asked for the reason, he said that a friend of his in Greece had just been arrested (remember that the military had taken over in Greece in 1967 and, I presume, in 1969 they were going through a rather virulent phase). I tried later, whenever I met "Van", to get details about the conversation but, as often in these cases (remember the recently made public Heisenberg-Bohr conversation of 1941), there was a nebulous cloud about it. Not even Marilena has been able to help. Be it as it may, Evangelos recovered from the phone call and the five of us (Evangelos, Aron, Eli, Fred, and myself, in that order) wrote the final version of a paper which appeared, of course, in *Solid State Communications* [1]. The subject was considered, at that time, rather esoteric and we did not expect that our paper would be seminal to many other publications, both theoretical and experimental, to the present date. With 236 cita-

tions over the years it became Evangelos's most cited publication and it gave a permanent imprint to his work. The paper has been cited this century already 20 times, having kept its impact 30 years after its having appeared. This became possible, of course, by the application of the then measured dependence of phonon frequencies on stress to the characterization of semiconductor nanostructures.

In 1971 Evangelos became an Assistant Professor at Northeastern University in Boston. In the face of the tough competition from Harvard, MIT, Boston University and other institutions in the area, his possibilities at Northeastern in terms of students and equipment, were limited. Characteristic of his activities in the years to follow, he looked for the equipment he needed elsewhere, where his expertise was usually received with open arms (outsourcing, as we call it today). So he spent the years 1973 and 1974 on and off as a visiting scientist at MIT, being promoted to Associate Professor at Northeastern in 1973. In spite of the limitations at that institution, I counted 30 publications which can be attributed to the Northeastern period. They cover a wide range of subjects, including infrared and Raman spectroscopy of lunar materials obtained in the Apollo 11,12,14 and 15 missions [2]. This work has been cited 43 times.

In November of 1973 the Military Dictator was toppled (I avoid mentioning his name so it does not appear as a citation in the Citations Index [3]) after a series of bizarre events which still today affect the Eastern Mediterranean. In July 1974 Karamanlis (he deserves to be cited!) became President and the long spook was over. Evangelos began to dream about a return and chose our Institute in Stuttgart as a vantage point from where to follow the events in Greece. I offered him a position in my group in the hope that he may stay here for a long haul, possibly permanently: I needed him rather badly. He arrived in Stuttgart in September of 1974 and plunged into the laboratory in spite of its being moved to a new site. But alas, his home country needed to rebuild the badly battered universities. He was appointed Associate Professor at the Technical University and given travel orders to start teaching in

Athens as of January 1, 1975. For me, it was a real "catastrophe", but he promised to come regularly to spend the summers in Stuttgart, which he did. The last collaborative effort before his untimely death was a 220 pages long article in "Semiconductors and Semimetals" [4] on the effects of uniaxial stress on phonons, the topic we had started in 1970.

One anecdote stuck in my mind from the short three-months period of his stay at the end of 1974. He came in the morning and showed me an infection, possibly staphylococci, in one of his fingers. It was rather ugly, the kind we call in the Catalan language *un voltadits*. We were just a five minute walk from the main hospital. I suggested that he go there and have them look at it. He did not return, so I called the hospital the next day and they told me he had spent the night there as an in-patient, was operated on, and was now waking up from "total anesthesia". I could not believe my ears. I went right away to the hospital and they told me that they had strict orders to operate all Greeks only under "total anesthesia". The reason, they claimed, is that Greeks, like all Mediterraneans, have a tendency to faint at the sight of blood and they did not want to take any chances. I have seen a lot of blood in my life and have never fainted!

I would like here to quote from the first letter which I received from Evangelos after his return to Greece, dated Jan. 30, 1975:

"Well, I made it all the way to Athens without any difficulty. My infection is also gone. Classes have already started; I have two 2-hour floor-shows (I mean lectures) every week. My audience consists of  $\sim 1000$  freshmen!! I feel like a political candidate. They are basically well-behaving, very much aware of what is going on, and extremely politicized. In addition to teaching, there is a lot to be done in running their labs, recitation meetings, and trying to reconcile the always complaining personnel."

My reply to him announced the positive solution of a serious bureaucratic problem. When he came in September of 1974 from the US, we had paid his transatlantic transportation. Before leaving in December he had been told by someone in our administration

that he had to return the fare because the law required for the refund a minimum stay with us of six months. This was a lot of money those days and the Greek government had apparently no legal means to pay the fare (unbelievable when you consider the cost of appointing and supporting a professor who is going to be active for at least 25 years!). So I wrote a strong letter to our administration in support of Evangelos, asking them to waive the refund with all kinds of more or less specious arguments. In a hand-written, informal, five lines note, the head of our administration answered me that there was no problem whatsoever. The corresponding paragraph of the law (a minimum stay of six-months for the refund) applied only to relatives, not to the visiting scientist. At least this time, German bureaucracy was allowed to act in a rational way.

I could fill a few more pages with anecdotes, some sweet, some sour. I remember we both having been invited to Wolfgang Richter's apartment on the occasion of his birthday in June of 2000. We left the party together, rather late, for our hotels and there were some seedy looking characters in the area. Evangelos insisted in delivering me to the door of my hotel. He was rather concerned with my personal safety: a premonition of his untimely death only a couple of months later? I remember very vividly what we talked about: Emmanuel Royidis and his famous 19th century novel. Those of you who know him may remember that Evangelos had an encyclopedic culture. We had discussed often the dearth of modern Greek literature till the end of the 19th century. He introduced me to Royidis and his raucously irreverent novel. I tried long to find a translation, to no avail. In January of 2000 I found one in a used book store in California [5]. By the time we last met in June, I had read it, so we had plenty of material to discuss. We spent about an hour at the door of the Hotel Heidelberg (the weather was mild) till he parted forever. He also recommended me to read the "Murderess", by A. Papadiamantis. I just found a German translation [6] and am in the process of reading it. Unfortunately, I will not be able to discuss it with Evangelos this time ...

Evangelos untimely death left a big hole in the lives of many of

us. First of all, I must think about his wife Marilena, then about the Technical University and even myself, who had known him since 1969, and collaborated with him regularly and steadily throughout those long years. But I do not think that Evangelos would like us to sit, wail and bemoan his death. He would implore that the moaning be left, like in the Greek antiquity, to professional wailers.

I would like here to celebrate Evangelos LIFE, to thank the powers that each of us believes in for having made him possible, and to celebrate and recall his important contributions to science.

## 2 Evangelos, the Scientist

As already indicated, Evangelos scientific life can be divided into four, partly overlapping periods:

1. The University of Pennsylvania (1962-1968).
2. Northeastern University (1969-1974).
3. The Max-Planck-Institute for Solid State Research in Stuttgart (1974 and a number of stays during the summers thereafter).
4. The National Technical University of Greece (1975-2000).

I shall present in what follows some highlights of his scientific work during those periods, the choice being guided by the criteria:

- What I consider to be the importance of the work.
- The citations the publication has received, according to a version of the ISI Web of Science (Institute of Scientific Information, Philadelphia) which encompasses the beginning of Evangelos career around 1965 (this version actually goes back to 1946!, so it even encompasses the beginning of Eli Burstein's career, except for two papers published by Eli in 1940 [7] and 1941 [8]).
- The work in which I have collaborated most intensely.

## 2.1 The University of Pennsylvania (Penn) (1962-1968)

The first and one of the most important publications of Evangelos [9], was based on work performed at Penn. It was co-authored by Eli Burstein, his thesis advisor, and Sato Iwasa, a bright Japanese graduate student who got his Ph.D. at Penn, also under Eli, in 1966. Sato moved then to the corporate sector and after a distinguished 25-years career with Lockheed and Honeywell, working mainly on infrared detectors and optical systems, founded his own company (IRtech Consultants, Harvard, Massachusetts) of which today he is still president.

Reference [9], a short letter, has been cited 32 times. However, to this number one must add 30 citations to a full-sized paper on the same topic published in 1970 [10]. I shall discuss next the main ideas behind this important and seminal work.

In 1965, laser Raman scattering was beginning to establish itself as a powerful technique for the investigation of elementary excitations in solids, in particular lattice vibrations (phonons). The technique was, at the time, mainly used to measure the frequency of such excitations (the so-called Raman shift [11]). Little attention was being paid to the scattering efficiency  $S$ , (defined as the ratio of the number of scattered photons per unit path length and unit solid angle to the number of incident photons). Only crude theoretical estimates already existed [12]. Evangelos first paper [9] led to the first experimental determination of  $S$  for a solid (diamond). It was an indirect method, based on a thermodynamic type of argument, and the numbers obtained have received ample confirmation in later, more direct work [13-17]. When comparing the dates of Ref. [1], (1966), with those of Refs. [13-17], (1970-1981,) we realize how far ahead of his time Evangelos was in 1966. This repeated itself a number of times later, especially in his work on piezo-Raman spectroscopy [1].

The “thermodynamic” argument used by Evangelos in [9] had been suggested by Burstein and Ganesan in 1955 [18], but had

to wait for two enterprising graduate students, Anastassakis and Iwasa, to bring it to fruition (Eli has also often been ahead of his time!). Phonon Raman scattering takes place through modulation of the electrical polarizability by the time-dependent amplitude of the phonon, as represented by the parameter  $a$  [with the dimensions of a length] which describes the derivative of the polarizability with respect to the phonon displacement. For the sake of simplicity, we shall here neglect the tensor properties of that derivative and represent it simply by the scalar  $a$  (given usually in Å<sup>2</sup>). The scattering efficiency  $S$  for diamond structure materials is then given by [1]:

$$S = r \frac{\hbar \omega_S^4 N^2}{\varrho \omega_0 c^4} |a|^2 (n_o + 1), \quad (1)$$

where  $r$  is a number of the order of one which expresses the scattering selection rules,  $\omega_S$  the scattered frequency,  $N$  the number of primitive cells per unit volume  $\varrho$  the crystal density,  $\omega_0$  the phonon frequency and  $n_o$  the Bose-Einstein statistical factor ( $n_o \simeq 0$  for diamond at 300K. According to (1) a determination of  $a$  leads to the determination of  $S$  and vice versa (except for the phase of  $a$  which in the region of transparency can only be zero or  $\pi$ , i.e.,  $a$  can be either positive or negative). The so-called Raman tensor  $a$  can be written as (dropping tensor indices):

$$a = \frac{\partial P}{\partial u}, \quad (2)$$

where  $P$  is the polarizability and  $u$  the sublattice displacement corresponding to the Raman phonon under consideration. Diamond has two atoms per primitive cell (PC), i.e., two sublattices. The phonon that corresponds to the displacement of one sublattice with respect to the other is Raman active, i.e., (2) does not vanish for it (there are actually three such phonons, corresponding to displacements along the three crystallographic directions). The middle point of the positions of the two atoms in a PC is a center of inversion that leaves the crystal invariant: it is said that the



corresponding phonons are *even* under inversion. Phonons can also be detected by infrared absorption spectroscopy: The absorption coefficient  $\alpha$  can be written as:

$$\alpha \text{ proportional to } \left| \frac{\partial M}{\partial u} \right|^2 \quad (3)$$

where  $M$  is the electric dipole moment of a finite piece of the crystal. Since  $\partial M/\partial u$  must be invariant with respect to symmetry operations and  $M$  is *odd* with respect to the inversion while  $u$  is even,  $\alpha$  vanishes for the Raman phonons of diamond (this is a rather general rule: for any centrosymmetric crystal, allowed Raman phonons are infrared forbidden, and vice versa). An electric field (odd symmetry) applied to diamond breaks the inversion symmetry and can make, in the absence of other symmetry restrictions, Raman phonons ir-allowed. The corresponding contribution to (3) is:

$$\Delta\alpha \propto \left| \left( \frac{\partial^2 M}{\partial u \partial E_0} \right) \right|^2 E_0^2 . \quad (4)$$

Considering that  $(\partial M/\partial E_0) = P$ , the term in brackets in (4) turns out to be precisely the ‘‘Raman tensor’’  $a$  of (2). Hence, a measurement of the ir absorption induced in diamond at the Raman phonon frequency by an electric field  $E_0$  yields a value for  $a$  and, using (1), for the scattering efficiency  $S$ . To measure this effect, the directions of  $E_0$  and the ir field  $E_{ir}$  must be judiciously chosen so as to avoid a vanishing of Eq.(4) imposed by symmetry selection rules. Evangelos chose  $E_0$  along the  $[001]$  crystallographic direction and  $E_{ir}$  along  $[1\bar{1}0]$ : it is easy to figure out that these directions yield the maximum  $\Delta\alpha$  for a given  $E_0$ .

Figure 1 shows typical experimental results for the effect of an electric field on the ir transmission of diamond, as obtained by Evangelos. The light path under the applied field,  $E_0 = 1.2 \times 10^5$  V/cm, was 2.4 mm. From the decrease of 1% in transmission seen in Fig. 2, a value of  $|a| = 3.8 \text{\AA}^2$  was determined in [9]. Note that

these measurements, as well as those of [10] and [13-17] do not yield information about the sign of  $a$  which is believed to be positive (the longitudinal polarizability increases when the C-C bond is stretched) on the basis of calculations [17].

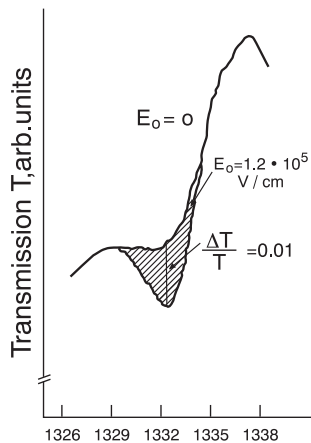


Figure 1: Recorded transmission spectrum for a diamond with a path length of 2.4 mm under zero and nonzero electric fields. The relative change of the transmittance is about 1% for  $E_0 = 1.2 \times 10^5$  V/cm [10]. See text.

The apex of experimental virtuosity was reached by Evangelos in [10] when he estimated, by using ac-techniques and lock-in amplifiers, the effect of order  $E_0^4$  on  $\Delta\alpha$  and that of order  $E_0^2$  on the Raman tensor.

The second most important piece of work of the “Penn Period” is probably contained in [1]. We reproduce the unprocessed experimental data in Fig. 3 so as to emphasize their quality, especially considering the rather unsophisticated equipment used.

Figure 3 shows spectra of the Raman phonon of silicon both, unstressed and under a *compressive* stress of  $11.5 \times 10^9$  dyne/cm<sup>2</sup> (1.15 GPa). Notice that under stress two peaks are seen, depending on the directions of incident and scattered light. Evangelos and I have given ever since to students the problem of figuring out which is

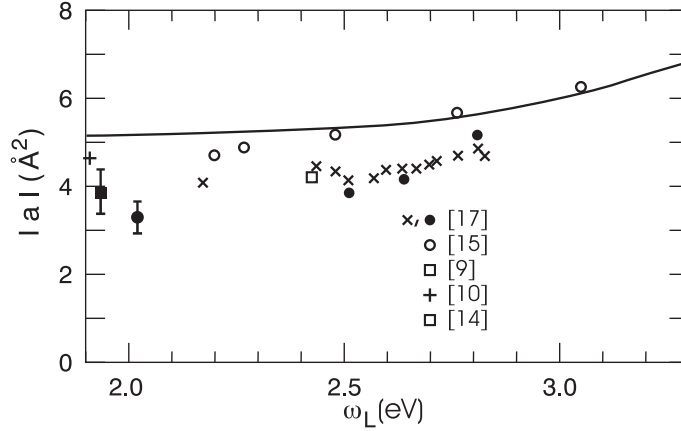


Figure 2: *Compilation of measurements of the Raman tensor and its dispersion for diamond. The solid line represents the equation  $a(\text{\AA})^2 = -6.5g (\omega_L/5.6 \text{ eV})$  discussed in [17]. According to this equation,  $a$  should be positive.*

the direction of vibration of the Raman phonons which correspond to either one of the two peaks. The answer good students find is that the peak obtained for incident and scattered polarizations parallel to the direction of the stress ([111] direction) corresponds to phonons which vibrate along that direction. For the other peak they vibrate perpendicular to it. A good student will soon add that this explains the direction in which the frequency shift takes place: if you compress along the direction of vibration the “springs” holding the atoms are compressed. They therefore get stiffer and the frequency should increase. This is correct for a compression along [111] but, as found in [1], for a compression along [100] the opposite takes place: the vibration along [100] *softens* while the perpendicular ones harden. It takes a very good student, such as Evangelos was in those days, to figure out the answer: A pure shear compression along [100] does not change the length of the bonds since it decreases it by an amount  $\Delta e$  along [100] and increases it by half as much along [010] and [001]. So far so good, but then the good student goes and measures diamond, as Evangelos did

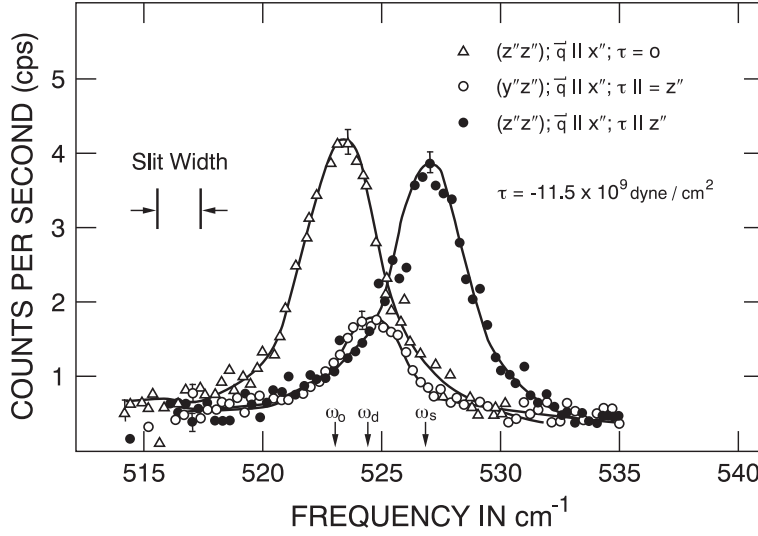


Figure 3: *The first-order Raman spectrum of Si at 300°K with a uniaxial stress  $\tau = -11.5 \times 10^9$  dynes/cm<sup>2</sup> applied along the [111] direction [1]. The entries in the parentheses, i.e.  $(z''||[111])$  and  $(y''||[1\bar{1}0])$ , designate the polarization direction of the incident and scattered radiation. In each case, the direction of the incident and scattered radiation is along  $x''$  ( $x''||[11\bar{2}]$ ) and  $-x''$ , respectively [1].*

years later, when he was no longer a student [19]. He, working in Stuttgart with Marcos Grimsditch [20] and myself, found that for diamond the longitudinal vibrations (parallel to the stress) increase in frequency for a compression either along [111] or [100]. Evangelos figured out a simple way to explain that: [19] diamond is much more covalent than silicon and therefore the restoring forces causing the lattice vibrations are not only strong for bond stretching, but also for bond bending. It takes a back-of-the-envelope calculation, of the type Evangelos excelled in, to show that under these circumstances the longitudinal vibrations also harden for a [100] compression [21]. He also pointed out years later [21], that the “anomaly” for a [100] compression also applied to boron nitride, a material closely related to diamond.

Representative for the 20-odd papers related to the "Penn Period", I would like to mention a series of five papers he published under the general title of "Morphic Effects, 1-5" [22-26]. It was a nice way of summarizing his experimental work on stress and field-effects on Raman phonons and presenting it under a unifying group-theoretical formalism. The collection of 5 papers has been cited a total of 120 times, a large number considering the dryness of the rather formal subject.

I conclude the "Penn Period" by mentioning another seminal piece of work having to do with electronic excitations in semiconductors [27]. Evangelos and co-workers observed electronic excitations of an electron gas introduced by doping with donors into bulk GaAs samples. Although this scattering is symmetry forbidden, it becomes observable when the exciting laser frequency is resonant with an electronic interband gap, in this case the  $E_0 + \Delta_0$  gap at about 1.9 eV. The observed scattering spectra depend rather strongly on whether the incident and scattered polarizations are parallel or perpendicular. For parallel polarizations, collective excitations, which reflect the Coulomb interaction between the electrons, are observed. In the perpendicular case, the scattering excitations involve a spin-flip and thus are not affected by Coulomb interaction: one observes single particle excitations.

## **2.2 Northeastern University in Boston 1970-1974**

The beginning of this period was spent in close collaboration with his former mentor Eli and some of the corresponding work has already been mentioned under 2.1. Evangelos work at Northeastern was influenced by the collaboration with Clyde Perry, who, after a varied and productive career in science and administration, is still in the Faculty at Northeastern [2,28].

In [28] work on ir-absorption and Raman scattering by two magnons (plus a phonon for the ir-absorption) in NiO was presented. In spite of the pioneer character of this work, it has been

cited only 12 times, a result of having been published in a rather obscure journal (although it was part of a memorial issue for C.V. Raman!).

To the Northeastern period belongs Evangelos brief excursion to the moon. Reference [2] has been cited about 50 times. In it he collaborated with Perry and R.P. Lowndes, who around 1970, became Dean of the School of Arts and Sciences at Northeastern, to remain in this position until 1997. The work describes a detailed analysis of moon rocks by optical spectroscopies, through comparison with similar rocks on earth. The authors concluded that the lunar rocks are mainly composed of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ , and  $\text{FeO}$ , some of them containing significant quantities ( $\sim 10\%$ ) of  $\text{CaO}$  and  $\text{TiO}_2$ .

Another paper belonging to this period was published in the prestigious journal “Science” [29]. The work was a collaboration among physicists and biochemists at Harvard, MIT and Northeastern. Two of the coauthors, K.J. Rothschild (a biochemist) and Eugene Stanley (a statistical mechanics theorist) are today highly reputable faculty members at Boston University. I.M. Asher was connected with Harvard and with the Food and Drug Administration Lab in Maryland. The paper describes the application of Raman spectroscopy to the determination of the structure of Valinomycin, an antibiotic. There was a follow-up to this work: two longer papers in the Journal of the American Chemical Society [30]. According to the byline, these papers fall already well into the Athens Period. I have not been able to figure out the logistics of such a collaboration.

As the last paper of this period, I mention his work with R. Greenwald [31], an undergraduate student at Northeastern who, following American custom (absent but much needed in Europe!), moved on as a graduate student to the University of Rochester. It contains beautiful work on optical properties of crystals, in particular  $\text{Bi}_{12}\text{GeO}_{20}$ . This material, which was rather topical at that time, has a cubic structure with the point group T, the least symmetric of all five cubic crystallographic point groups. As a consequence of the

lack of reflection planes, crystals belonging to this group are *chiral* and exhibit optical rotatory power (i.e., they rotate the plane of polarization of linearly polarized light). Greenwald and Anastassakis measured the optical rotatory power of  $\text{Bi}_{12}\text{GeO}_{20}$  vs. wavelength and the effect of pressure and temperature on this unusual but important property. The results were interpreted on the basis of a single oscillator which was allowed to depend on temperature and pressure. In spite of the somewhat esoteric nature of  $\text{Bi}_{12}\text{GeO}_{20}$ , [31] has been cited 35 times.

## 2.3 Athens

As already mentioned, Evangelos moved in 1974 from Boston to the Max-Planck-Institute in Stuttgart and, after three months, continued to Athens. Until his death he kept also contact and collaboration with my group in Stuttgart and also that of Wolfgang Richter in Aachen and Berlin [32]. He had met Richter in Philadelphia, where the latter was a post-doc with Eli, and met him again in Stuttgart while Richter was working in my group: an example of “the web of science”. This section highlights the work that Evangelos and his Greek associates performed in Athens. Section 2.4 will discuss some of the work that resulted from his collaboration with my group in Stuttgart.

When Evangelos arrived to the National Technical University in 1975, he had no experimental facilities. Moreover, there were more pressing duties than experimenting: he had to lecture to over 1000 students, as you read in Sec. 1, and he had to help repair the ravages of seven years military dictatorship. Money for research was nonexistent: he had to help develop in the political class the awareness for the need of scientific, especially physics, research: this may sound paradoxical for the country where physics was invented. In order to stay fit, Evangelos began doing paper-and-pencil work in Athens and traveling, during the holidays, to some of the more fortunate friends who had experimental facilities [32]. Slowly, but surely, he got money to set up a modest lab in Athens where, by the

early 1980's, he had a Raman spectrometer and a diamond anvil cell to do optical work under high hydrostatic pressure. By the mid 1980's experimental work performed in his Athens lab began to appear in the international literature. I would like to mention from this period the work with Liarokapis [33] in which they measured the effect of intrinsic carriers, excited across the small gap of InSb at high temperatures, on the phonon Raman spectrum of InSb. Another publication, with Liarokapis and Kourouklis [34], presents Raman data for  $\text{LaF}_3$  vs. temperature and pressure. The  $\text{LaF}_3$  crystals, with rhombohedral space group  $D_{3d}^4$  under ambient conditions, display rather unusual anharmonic behavior vs. pressure and temperature. Raman measurements under pressures up to 10 GPa (100 kbar) were performed in Athens at 300K and in Stuttgart, in a solid argon environment, at 25K so as to check the consistency of the results. I would have liked to share with Evangelos our recently gained understanding of the temperature behavior of phonon self-energies [35] and reinterpret with him the interesting data which he published in [34].

More piezo-Raman work, in which Kourouklis and Evangelos discovered a phase transition in  $\text{SrF}_2$  at 300K, appeared in [36]. In [37] Anastassiadou, Raptis and Evangelos discuss the effect of absorption and angular spread on Raman scattering and compare the calculations with results they obtained for GaAs, including the TO-LO splitting and the electrooptic effect on the LO-scattering. Similar calculations had been performed by the group of Miles Klein at the University of Illinois, at Urbana [38] using a different approach. The equivalence of the two methods is not obvious and should be investigated.

Around 1986 Evangelos realized that Raman scattering was an excellent technique for characterizing stresses and strains in semiconductor nanostructures. He had actually laid the basis for this work in [1] and decided to apply his mastery of crystal optics and tensor analysis to develop a general formalism which could be used with as little computational effort as possible. In [39] Anastassakis and Liarokapis developed a formalism for evaluating the splitting



of phonons, equivalent to that of Fig. 3, but for a polycrystalline sample. Considering the strong anisotropy of such splitting, already mentioned in connection with Fig. 3 and discussed in [1], complex tensor averages must be performed. This work is a real “tour de force” in tensor analysis of crystal properties. It has been cited 40 times. Another highly cited publication [40] presents general expressions to calculate built-in strains at heterojunctions of arbitrary origin due to lattice mismatch. Evangelos and I were, at the time, unhappy about using the term *biaxial* strains for isotropic strains in two dimensions. He came up with the term *bisotropic* which he used consistently ever since, as opposed to the commonly employed but misleadingly incorrect designation of *biaxial*.

Going through the literature while writing this article, I discovered a paper [41] in which a detailed but simple modeling of the optical properties of diamond in the region of electronic interband transitions (0-25 eV) was presented. I was surprised to see that in it Evangelos has collaborated with *Papadopoulos*, but soon I realized that it was A.D., not G. Although this article has been cited 20 times, it was unknown to me. Had I known it, I would have used it in some of the more recent work I have done for diamond [42]. My apologies, Evangelos.

Last, but not least, I would like to mention the contribution of Evangelos to the success of the memorable 20th International Conference on the Physics of Semiconductors (20-ICPS), which was held in Thessaloniki in August of 1990. The Proceedings of the 20-ICPS [43] were edited by Evangelos, together with J.D. Joannopoulos, a well-known faculty member at MIT who has distinguished himself recently by excellent work on photonic crystals. I found in the citations index several papers from those proceedings with a remarkable number of citations, contrary to popular belief that conference proceedings are never cited. I fear, however, that this “popular belief” may become a self-fulfilling prophecy, if the present trend to electronic publishing continues [see Proceed. of 24-ICPS (Jerusalem) and the 26-ICPS (Edinburgh)].

## 2.4 Athens-Stuttgart Collaboration

This fruitful collaboration lasted for a quarter of a century, from 1974 until Evangelos death. The “logistics” was often that he came to Stuttgart for a couple of months, collected data and helped with their processing and the writing of a manuscript after returning to Athens. The first such collaboration involved measurements of the pressure dependence of the LO and TO frequencies of GaAs with the diamond anvil cell [44]. It was probably the first contact of Evangelos with this powerful device. A mixture of methanol and ethanol was used in those days as a pressure transmitting fluid, a pressure fluid which since has been replaced by helium because of the problems involved in the stiffening and freezing of alcohols under pressure. Nevertheless, the results Evangelos obtained working with Rainer Trommer, a German graduate student now at Siemens (see Fig. 4), stand today as correct [44]. Once more against popular belief, the work has been cited 50 times, in spite of having appeared in the proceedings of a conference. The conference was held in Campinas, Brazil, at the time of a rare economic boom in that country which allowed the organizers to pay the air fare of basically all participants (of course on VARIG, a Brazilian airline). I recall that about 10 researchers from my group, including several graduate students, belonged to this category, something that had never happened before and probably will never happen again. I believe that Evangelos was also there. This work confirmed our conjecture that the effective charge  $e^*$  decreases under pressure in most semiconductors and led us to develop a simple-minded explanation of this non-intuitive fact based on the so-called *Laffer curve* (Fig. 5).

This curve was allegedly suggested by Arthur B. Laffer at a dinner party in 1974, drawing it on a napkin, in order to explain the dependence of the state revenue on tax rate: if the tax rate is to the right of the maximum, its increase will lead to a decrease in revenue and vice versa (the people who believe this are called “right wingers”). The opposite is true if the operating point is

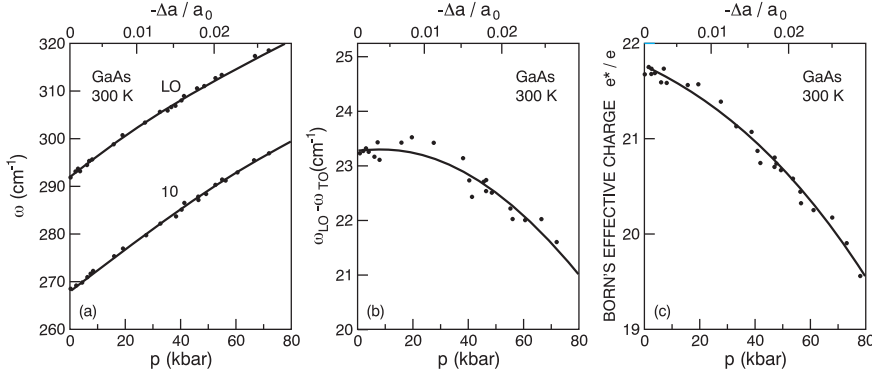


Figure 4: *Effect of hydrostatic pressure on (a) the LO and TO Raman frequencies of GaAs. (b) The difference between the  $\omega_{LO}$  and  $\omega_{TO}$  frequencies. (c) Born's effective charge vs. pressure as obtained from the data in (a) and (b) [44].*

to the left of the maximum. Laffer became economic advisor to Ronald Reagan who, being a “right winger”, decided on the basis of Fig. 5 to lower the taxes so as to increase the internal revenue of the US. The results of the experiment are well known.

In any case, the Laffer curve can also be taken to represent the behavior of the ionicity of GaAs, i.e.  $e_T^*$ , vs. pressure. The ionicity is zero for infinite lattice parameter since Ga as well as As must then be neutral. It is also zero for a hypothetical lattice parameter zero, since no charge transfer from Ga to As can occur. Whether  $e_T^*$  increases or decreases under pressure (i.e., when the lattice parameter decreases) depends on the position of the equilibrium lattice parameter with respect to the maximum of the Laffer curve ...

Because of the already mentioned increasing interest in the effects of uniaxial stress on phonons in semiconductors, pioneered by Evangelos in [1], he took up in Stuttgart new aspects of this problem, in particular those privy to ir-active phonons. In [45] he collaborated with Paul Wickbold and Rolf Sauer [46]. Paul Wickbold had just finished his B.Sc. at Stony Brook and was spending a few months in Germany, the land of his ancestors, before going

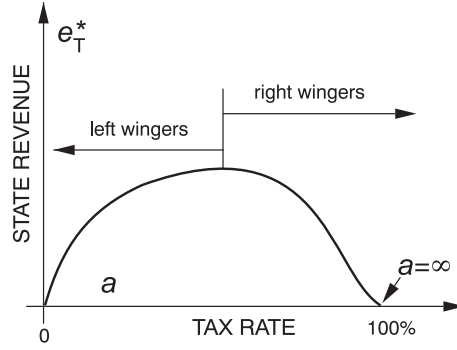


Figure 5: *Curve proposed by Laffer (Laffer's Curve) to represent the state revenue as a function of tax rate. It has been used by Anastassakis and myself to represent the dependence of Born's effective charge  $e_T^*$  on lattice parameter  $a$  (Fig. 4c). See text.*

to work at Harvard with my former thesis advisor, Bill Paul (the Web of Science again).

The splitting of TO and LO phonons of GaAs by a uniaxial stress along [111] reported in [45] is shown in Fig. 6. An alert student will understand why the TO phonons, a doublet, split. He will, however, ask how come the LO phonon, a singlet, also splits. A *very* alert student may find the answer: the LO and TO phonons are not only characterized by the direction of *vibration* but by that of *propagation*. The LO nomenclature implies that the vibration is *parallel* to the propagation direction, whereas it is perpendicular for the TO-phonons. Hence, there are three degenerate LO phonons under zero stress: one which vibrates and propagates along [111] and two which do both things perpendicular to [111]. When a stress along [111] is applied, this triplet splits into a singlet (propagating and vibrating along [111]) and a doublet (doing both things perpendicular to [111]). This is expressed by the *s* and *d* subscripts in Fig. 6. The splittings of both phonons in Fig. 6 correspond to the splittings shown in Fig 1 for silicon but again, the alert student will note that the  $\omega_L$  and  $\omega_T$  splittings are not equal in Fig. 6. This was explained by Wickbold, *et al.* as reflecting the anisotropic effect of

the strain on  $e_T^*$  for which a phenomenological theory was developed in [45]. These effects are nowadays calculated *ab initio* on the basis of the electronic band structure [21], nevertheless phenomenological models can be very useful to trace errors such as those pointed out in [21]. Reference [45] has received 86 citations.

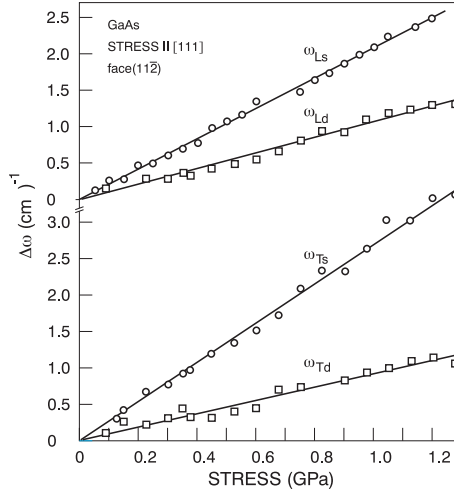


Figure 6: *Splittings and shifts reported in [45] for the TO and LO phonons of GaAs under a uniaxial stress along [111]. The subscripts d and s correspond to vibrations perpendicular and parallel to the stress direction (see text).*

Most of Evangelos publications on the subject of stress effects on phonon frequencies have been highly cited. Belonging to the Athens-Stuttgart period I would like to mention the work on diamond [19], already discussed in Sect. 2.1, in connection with [1]. This work has been cited 110 times!

I would like to close the discussion of the Athens-Stuttgart period by mentioning a paper [47] which, in spite of being rather recent (1997), has nevertheless been cited 21 times. This paper belongs already to the era of *ab initio* calculations but stands as a *caveat* to *ab initio* calculators that not everything they calculate needs to be correct. Note the break in the calculated linewidth vs.

pressure at 7GPa, which is not shown by the experimental data, a fact which was attributed in [47] to a slight error in the calculated frequencies of the two-phonon decay channels which are responsible for the phonon width. This error can be corrected by hand: the correction is represented by the dashed-dotted line in Fig. 7. This discrepancy, and the correction of the theoretical results so as to agree with the experimental ones, is best expressed by a sentence which is attributed to Max Planck, but could also have been Evangelos's:

“Experiments are the only means of knowledge to our disposal. The rest is poetry, imagination.”

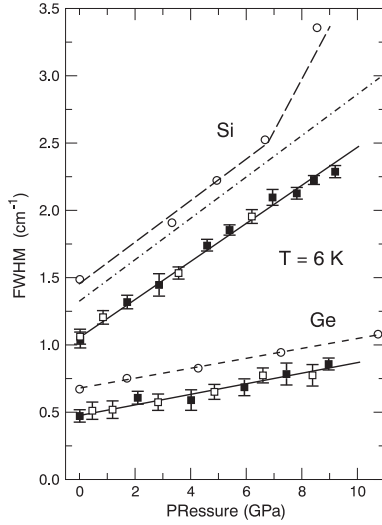


Figure 7: *Measurements of the dependence of Raman phonon linewidths of Si and Ge on pressure (symbols with error bars) as reported in [47]. The empty circles with dashed lines across represent ab initio calculations: note the break for Si at  $\approx 7$  GPa which is an artifact of these calculations. The dashed-dotted line represent the calculations after removal of the artifact.*

### 3 Conclusions

In this article I have tried to portray Evangelos life as a human being, a friend, and a scientist from the vantage point of our 32 years of friendship and collaboration. The Web of Science lists 26 papers jointly authored by Evangelos and myself. They are among the most cited of his and my publications and, as such, many appear in the enclosed list of references. I (and posthumously Evangelos) would like to thank the many collaborators spread around the world (our Web of Science) who made these publications possible even if they have not been explicitly mentioned (many have). His untimely death dealt a severe blow to Greek science. We all miss him, but he will be mostly missed by his wife Marilena. Let me thank her, in the name of us all, for the invaluable support she gave him.

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- [3] After writing this sentence, I consulted the Citations Index. Under G. Papadopoulos I found 297 titles with a total of 2417 citations. Although in the heyday of his dictatorship they may have been attributed to “you know who”, it became clear to me that this name is rather common in Greece. The citations were to papers covering almost the whole range of human endeavor, from theology through medicine, from food technology to quantum gravitation. Scientists with that name are spread over the five continents. Nevertheless, I only found two references to the infamous Georgios, with a single citation each. One was to an opuscle called *Democracy Greek Face (sic)*, published in 1969. The other to a book called “He Hellenike Nyrenverge”.

In view of the large number of homonyms of G.P., and knowing that Anastassakis is a common name in Greece, I did a search of citations for all Anastassakis. I only found one significant author, a zoological biochemist from Canada, P.A. Anastassakis, specializing in poultry, pork, fish and the like. He had a total of 255 citations, insignificant when compared to Evangelos’s over 3000 citations.



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